

Mitigating Fatal Accidents: The Critical Role of Optimal Site Supervision Allocation for Construction Workers of Varying Ages, Education, and Experience

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ABSTRACT

Recent research indicates that accidents involving construction craft workers with lower educational attainment, experience levels, and older workers are significantly more likely to result in fatal injuries. This issue is prevalent in many construction projects due to the reported shortage of skilled labor and the increasing age of craft workers worldwide. This study quantitatively investigates the impact of site supervision on the severity of construction accidents, specifically focusing on whether it can reduce fatal injuries among craft workers with varying levels of age, education, and experience. The current study analyzed data from 6,336 construction accidents in Tehran Province, Iran, between 2011 and 2017. Statistical methods were employed to examine the relationship between site supervision and the severity of accidents, considering the different characteristics and capabilities of the craft workers involved. The findings indicate that site supervision is statistically associated with reduced accident severity, particularly among craft workers with lower age, education, and experience. This association is less pronounced among older, more educated, and more experienced workers, who may better manage their own safety. This study is novel in its empirical examination of the preventive role of site supervision in fatal construction accidents, relative to the characteristics and capabilities of craft workers. It highlights the need for targeted supervision based on worker demographics, offering insights that are particularly valuable in the context of the global shortage of skilled labor and aging construction workforce.

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1. Introduction

Construction is a hazardous industry where workers' health and safety always require critical attention from both practitioners and academic researchers worldwide [1]. Annually, over 60,000 fatalities are reported from construction projects globally [2]. Safety accidents within this industry not only lead to numerous injuries and fatalities but also severely disrupt project operations [3]. Despite significant advances in safety management research, unacceptable injury rates in construction continue to be a worldwide pattern [4].

Recent research has shown that some safety leading indicators and precursors can be used to predict construction projects' safety performance with an acceptable level of confidence [5]–[7]. However, this trend of research is in its early stages of development. Among the numerous factors influencing construction safety performance, site supervision is the one that has been frequently highlighted in the past literature [8]. Recent research has completely refuted claims regarding the ineffectiveness of supervision in safety incidents [9]. Weak supervision, both independently and in combination with other factors such as inadequate training, has a significant impact on the occurrence of safety incidents [10].

To better understand the role of site supervision in project safety performance, its influence through different perspectives of construction safety studies will be examined. Hallowell et al. recognized four major perspectives in safety research in the past literature [11]. These perspectives were recognized by Hallowell et al. and classified in four major groups in past literature which are: 1) safety risk assessment, 2) precursors analysis 3) safety leading indicators, and 4) safety climate.

1.1. Site Supervision in Safety Risk Assessment Perspective

The impact of supervision on hazard recognition and risk perception has been clearly demonstrated in a recent review article [12]. Wong et al. defined inadequate supervision as a condition in which crew members fail to identify hazardous situations and hence, will be unsuccessful in controlling associated safety risks. Supervisors and safety managers are responsible for the process of risk assessment through the site inspection [13]. They also should be involved in the process of job hazard analyses and communicating the hazards to the workers [14].

Xia et al. developed a model based on the Human Factors Analysis and Classification System (HFACS) to predict safety performance in construction projects. They, first, recognized 18 risk factors from organizational, environmental, and human aspects and then categorized them into five levels. The third level in this model is “unsafe supervision and monitoring” which includes inadequate supervision, supervisory violations, and inadequate dynamic monitoring [15]. The relationship between unsafe supervision and monitoring and all four other factors with project safety performance was validated with opinion-based data and also with subway project data. Winge et al. investigated 174 relatively severe construction accidents. In this study, immediate supervision again was recognized as one of the most important causal factors of accidents which strongly influence the worker's actions [16].

1.2. Site Supervision in Precursors Analysis Perspective

Precursors can be broadly defined as conditions, events, and sequences that precede and lead up to an accident. [17]. Pragmatically, precursors are considered warning signs that precede accidents [18]. Site supervision has been recognized as one of the precursors of serious accidents in construction worksite [19]. It should be noted that the focus of precursors is mainly on the condition of the workforce rather than management practices which distinguishes them from leading indicators [11]. For instance, the precursors related to site supervision focus on the knowledge, competencies, and capabilities of supervisors in managing safety issues while the leading indicators related to site supervision focus on the objective and measurable management practices such as frequency of walkthroughs in the worksite. Alexander et al. conducted an intensive literature review and identified 43 potential precursors for construction fatalities [20]. Among these potential precursors, the following factors directly relate to the site supervision: 1) supervisor incompatibility (refers to the relationship between crew members and their supervisor), 2) limited safety supervision, and a poor quality or inexperienced supervisor.

1.3. Site Supervision in Leading Indicators Perspective

Leading indicators, which are about the quantity of safety management practices, can be defined as a set of measures that describe the level of effectiveness of safety processes in a construction project [21]. In the majority of research studies about safety leading indicators, site supervision is recognized as one of the most influential leading indicators. Alruqi and Hallowell conducted a meta-analysis on empirical safety research studies and identified nine common leading indicators with significant correlation to worksite injuries [22]. Among these nine factors, they recognized “frequent safety inspection and observation” as a leading indicator that has the largest influence on injury rate reduction.

Liu et al. investigated the influence of owner practices on construction safety and identified six vital factors related to owner safety practices called critical to safety (CTS). Applying the analytical hierarchy process, they found that safety experts in their study placed the most stress on CTS of “monitoring contractor safety compliance”. This CTS contains nine measurements about safety monitoring in the work site [23]. The other opinion-based studies emphasize on the site supervision as a noteworthy leading indicator [24]–[26].

1.4. Site Supervision in Safety Climate Perspective

Safety climate is concerned with the shared perceptions and beliefs that craft laborers preserve about safety in their workplace [27]. Mohamed conducted a study to examine the relationship between determinants of construction site safety climate and overall safety climate, and also the influence of safety climate on the safe work behavior of craft laborers in worksites. Mohammed identified 10 constructs for construction site safety climate and found the supervisory environment as one of these constructs which have significant influence on the safety climate [28]. This construct was measured with seven questions concerning the safety perception of craft workers regarding behavior, safety attention, and safety competency of supervisors in the worksite. Similarly, Fang et al. conducted a study on the safety climate in the construction industry of Hong Kong and recognized the significant role of a supervisor in the worksite safety climate [29].

In addition, three studies specifically investigated the influence of site supervision on worker safety behavior. All these studies explain that this influence will be through project safety climate. Zohar and Luria demonstrated that increased safety-oriented interaction of supervisors with their subordinates resulted in significant improvement in safety climate and worker’s safety behavior [30]. Fang et al. tried to examine the effect of supervisory behavior on worker safety behavior in construction projects. Analyzing 262 questionnaires, they found safety climate serves as a mediating variable in the influence of supervisor behavior in improving worker safety behavior [31]. Liang and Zhang also analyzed 300 questionnaires from construction workers and demonstrated that workers are more likely to break safety rules when they perceive their supervisors have safety violations [32]. In this study, the influence of site supervision again was proved with the mediating effect of perceived safety climate. Fig.1 illustrates the processes of the influence of site supervision on project safety performance through four current major perspectives of safety research studies.

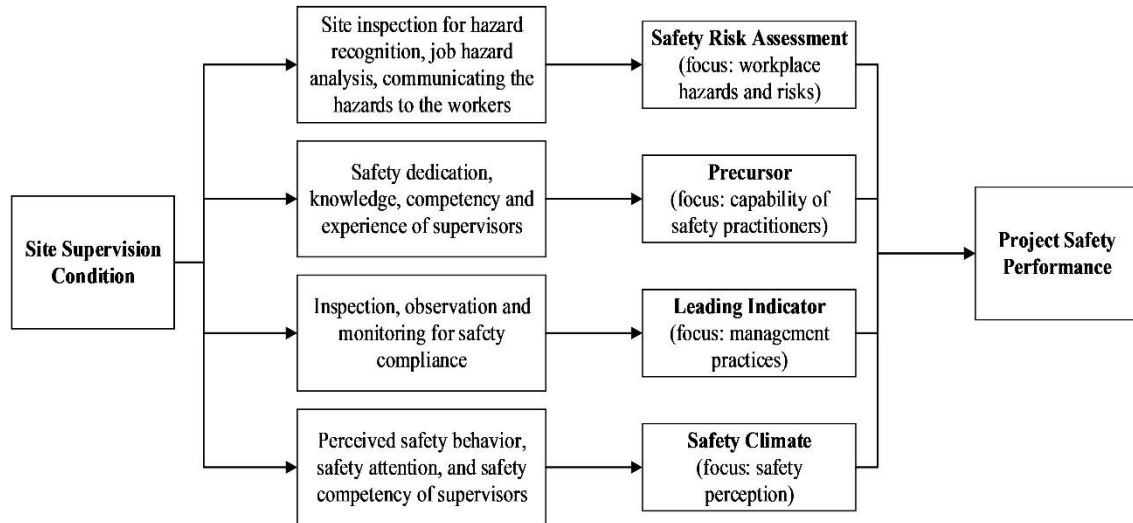


Fig.1 The processes of the influence of site supervision on project safety performance are classified in four different perspectives of current construction safety research studies.

1.5. Influence of Site Supervision on Fatal Injuries Prevention in Construction Projects

In addition to the studies that discuss the overall influence on safety performance, there are a few studies that specifically discuss the preventive influence of site supervision on fatal injuries. Chan et al. investigated 22 fatal falls from height accidents, analyzing them based on 12 factors. They recommended five strategies to prevent similar accidents, with providing safety supervision being identified as the third-tier preventive measure [33]. Alexander et al. analyzed 19 fatal accidents and identified 16 precursors to predict high-impact events in construction. Two key precursors related to site supervision are "limited safety supervision" and "inexperienced foreman," highlighting the importance of supervisor dedication, availability, and expertise in safety matters [34].

Age and experience play significant roles in construction accidents. The study, which analyzed 338,173 occupational accidents recorded in Turkey's construction industry, highlights that worker-related factors such as age and experience significantly influence the likelihood of fatal accidents. According to Koc et al., inexperienced workers or those in extreme age ranges are more susceptible to severe accidents [35].

The body of literature provides strong qualitative and quantitative evidence on the role of site supervision in improving construction safety performance. This influence has been analyzed through various frameworks, including safety risk assessment, precursors analysis, safety leading indicators, and safety climate. Additionally, several studies on fatal accidents have identified inadequate site supervision as a primary contributing factor. However, existing research has not quantitatively examined the extent to which site supervision mitigates fatal accident risks across different worker demographics.

Furthermore, past studies did not consider the prevalent problems of a shortage of skilled workers and the aging of craft workers in the construction industry. The chance of having fatal accidents in projects executed with old workers and/or less experienced/educated ones will increase significantly [36], [37]. In addition, regarding characteristics of site supervision provided in the previous section, it is expected that achieving adequate site supervision will require proficient supervisors and other resources, which may not always be available in all construction projects. This study addresses the identified research gaps by introducing the following key contributions:

- Quantitative assessment of supervision impact: Unlike previous research, this study employs a large accident dataset and statistical methods to measure the extent to which site supervision reduces fatal accident risks.
- Demographic-specific analysis: The research goes beyond a general evaluation of supervision effectiveness by

examining how its impact varies across different age, experience, and education groups of craft workers.

- Strategic workforce safety management: By identifying which worker demographics (young, inexperienced, or less-educated) are most dependent on supervision for accident prevention, this study provides practical insights for optimizing supervision allocation and workforce planning. The findings help construction managers develop data-driven policies for distributing supervisory resources more effectively, especially in projects facing supervisor shortages, skilled labor shortages or employing high-risk workers.

2. Research Methodology

2.1. Research Aims

This study contributes to the body of knowledge by quantitatively examining the preventive strength of site supervision on fatal accidents in craft workers with different levels of educational attainment, skill/experience levels, and different ages. In other words, the study attempts to examine the impact of inadequate site supervision in exacerbating the consequences of accidents to fatal injuries. This argument has been made by Reason discusses that in the presence of latent conditions (e.g. lack of site supervision), the occurrence of more severe accidents is expected due to the adverse impacts of deficiencies on the system's defenses and barriers [38].

To accomplish the aims of the study, the following objectives were defined:

- To identify whether, overall, adequate site supervision can significantly diminish the severity of accidents from fatal to non-fatal ones.
- To investigate the effectiveness of site supervision in preventing fatal injuries in craft workers with different levels of education, skill/experience, and different ages.

Based on these objectives, the study formulates the following hypotheses:

Hypothesis 1: Adequate site supervision is significantly associated with reduced odds of fatal accidents in construction projects.

Hypothesis 2: Adequate site supervision is significantly associated with reduced odds of fatal accidents across all education levels of craft workers.

Hypothesis 3: Adequate site supervision is significantly associated with reduced odds of fatal accidents across all experience levels of craft workers.

Hypothesis 4: Adequate site supervision is significantly associated with reduced odds of fatal accidents across all age groups of craft workers.

2.2. Data Source

The data used in this study were obtained from the official database of accidents collected by the Department of Labor Inspection of the Ministry of Labor and Social Affairs of Iran. This database includes accidents that occurred in construction projects performed in the Tehran Province, Iran, between 2011 and 2017. Accident reports were compiled by qualified labor inspectors following every reported incident, regardless of the reporting source (e.g., forensic medicine, law enforcement, labor department, fire department, hospitals, etc.). While no independent third-party verification was conducted, the reports were prepared in a standardized format for official labor inspections, ensuring consistency and completeness. As a result, no missing or incomplete data were present in the dataset.

Although the dataset used in this study has been analyzed in previous research by Karimi and Taghaddos (2019, 2020), the present study provides a distinct analytical and conceptual contribution. The first study focused solely on the individual effects of education and experience on fatal accident prevention, without considering the role of site supervision [36]. Similarly, the 2020 study examined how age moderates the relationship between education, experience, and accident

outcomes [37]. The second study introduces the concept of site supervision as a potential moderating factor and investigates its association with accident severity across different subgroups of craft workers defined by age, education, and experience levels. By doing so, this study provides a novel framework for understanding how supervisory presence interacts with worker characteristics in shaping safety outcomes. Additionally, it offers practical policy implications, highlighting the need for targeted supervisory strategies based on worker demographics, a dimension not addressed in the prior work. Thus, despite the reuse of the dataset, the present study offers new analytical insights and implications relevant to both researchers and construction safety practitioners.

In this study, adequate site supervision was determined based on assessments conducted by labor inspectors from the Department of Labor Inspection. These inspectors evaluated supervision adequacy through on-site visits using their professional judgment, informed by general safety principles and experience. While their evaluation considered factors such as the presence, qualifications, and involvement of supervisors in risk mitigation, it was not based on a standardized checklist or quantitative scale. As such, the classification of supervision adequacy in this study may reflect inherent subjectivity and variation across cases.

The total number of available accidents was 6,336. Among these accidents, 1400 were fatal accidents and 4,936 were non-fatal ones. It should be noted that for certain reasons, such as difficulty in reporting and/or unfamiliarity of craft workers with their rights, it is highly likely that non-fatal accidents in this database were underreported. This is not an issue that merely happened to this accidents database and the same issue has been reported in other countries such as the United States (The Center for Construction Research and Training, 2013). In this study, it is reasonably assumed that the underreporting issue in non-fatal accidents has a similar pattern across all groups of craft workers, which will be classified in the next section for the purpose of data analysis; Therefore, the result of analysis will remain valid and reliable.

2.3. Educational Attainment, Experience Level, and Age Classification of Craft Workers

The classifications of craft workers in educational attainment, experience/skill level, and age were based on what has been defined in two recent studies by Karimi and Taghaddos (2019, 2020). These classifications are shown in Tables 1, 2, and 3.

Table 1. Craft Labor Age Classification

Group No.	1	2	3	4	5	6
Age Interval (yr.)	16-24	25-34	35-44	45-54	55-64	65-75

Table 2. Craft Labor Educational Attainment Classification

Group No.	Education Level	Years of Schooling
1	Primary School or Less	0 or 5
2	Above Primary School but Lower than High School Diploma	8 or 10
3	High School Diploma & Above	12, 14, 16 or 18

Table 3. Craft Labor Skill/Experience Classification

Group No.	Experience Level	Experience (years)
1	Entrance to Industry & Training	0 – 3.99
2	Semi-Skilled/Experienced	4 – 9
3	Skilled/Experienced	> 9

All accidents in this database have been inspected by proficient official inspectors of the Department of Labor Inspection. After a complete investigation, inspectors provided their overall judgment about whether the worksite had adequate site supervision (i.e., Yes/No). Therefore, craft workers who experienced an accident can be divided into two

groups: 1) craft workers who experienced an accident while working under adequate site supervision conditions and 2) craft workers who experienced an accident while working under inadequate site supervision conditions. It should be noted that, as discussed before, the adequacy of site supervision can be assessed based on several practices of different parties, of contractors, subcontractors, owners, and safety consultants.

2.4. Statistical Methods and Justification

To test the research hypotheses, the Chi-Square Test of Independence and Odds Ratio (OR) analysis were employed. The Chi-Square Test of Independence was used to determine whether a significant relationship exists between site supervision adequacy and accident severity (fatal vs. non-fatal) across different worker demographics (education, experience, and age). This test was chosen because it is well-suited for analyzing relationships between categorical variables. The test satisfies the three main assumptions required for validity [39]:

1. Categorical variables: Both site supervision adequacy (adequate/inadequate) and accident severity (fatal/non-fatal) are categorical.
2. Random sampling: The dataset consists of accident records collected systematically from various sources, ensuring a representative sample.
3. Expected frequencies: In all cases, the expected frequency for each cell in the contingency table was ≥ 5 , satisfying the assumption for Chi-Square analysis

In addition to the examination of associations between variables, the strength of associations can also be measured with the odds ratio. The farther the value of θ from 1 represents the stronger the association between two categorical variables. [39].

3. Results and Discussion

3.1. Hypothesis No.1: Association between site supervision adequacy and the reduced odds of fatal accidents

The purpose of the first hypothesis testing is to assess whether site supervision adequacy is statistically associated with accident severity (the odds of fetal accidents). Accidents in the database can be divided into two groups: 1) accidents that occurred in the worksite with adequate site supervision and 2) accidents that occurred in the worksite with inadequate site supervision. The Chi-Squared Test of Independence was performed to examine the relationship between site supervision conditions and the severity of the accident (fatal/nonfatal). As mentioned before, it is highly likely that some non-fatal accidents were not reported and hence not documented in the database. It is reasonably assumed that the underreporting issue for nonfatal accidents has the same probability in the two groups; therefore, the validity of the analysis will remain unaffected. The null hypothesis of the test is that there is no relationship between the two variables. The alternative hypothesis is that there is a significant relationship between site supervision conditions and the severity of accidents (fatal/nonfatal). The alternative hypothesis was determined by obtaining a p-value of less than 0.05. As shown in detail in Table 4, the analysis indicates that adequate site supervision is statistically associated with a shift in accident outcomes from fatal to non-fatal injuries.

Table 4. Hypothesis testing results on the association between site supervision adequacy and the reduced odds of fatal accidents among construction craft workers

Number of Accidents	No. Fatal No. Nonfatal Fatal/Total Odds Ratio	Site Supervision		Pearson Chi-Squared Test		
		Inadequate	Adequate	Value	df	P-value
6336	Fatal	1084	316	13.165	1	0.000
	Non-Fatal	3583	1353			
	Fatal/Total	23.23%	18.93%			
	Odds Ratio	1.30				

Note: The value of fatal/total is not accurate as it is expected that there were underreporting issues in non-fatal accidents.

3.2. Association between site supervision adequacy and the reduced odds of fatal accidents among craft workers with different levels of educational attainment

The second hypothesis examines whether an association exists between site supervision adequacy and the reduced odds of fatal accidents across all education level groups of craft workers. The analysis shows that this association is statistically significant only among workers with low educational attainment (fewer than 5 years of schooling), where adequate supervision is linked to reduced odds of fatal injuries. No statistically significant association was found in the other two education groups (Table 5).

Table 5. Hypothesis testing results on the association between site supervision adequacy and the reduced odds of fatal accidents in craft workers of different educational attainment levels

Group number	Years of schooling	Number of accidents	No. Fatal No. Non-Fatal Fatal/Total Odds Ratio	Site Supervision		Pearson chi-squared test		
				Inadequate	Adequate	value	df	p-value
1	(0 – 5)	3601	Fatal	834	226	10.962	1	0.000
			Non-Fatal	1866	675			
			Fatal/Total	30.9%	25.1%			
			Odds Ratio	1.33				
2	(8 -10)	1621	Fatal	164	58	0.824	1	0.205
			Non-Fatal	992	407			
			Fatal/Total	14.2%	12.5%			
			Odds Ratio	1.16				
3	(12-18)	1114	Fatal	86	32	0.000	1	0.540
			Non-Fatal	725	271			
			Fatal/Total	10.6%	10.6%			
			Odds Ratio	1				

3.3. Hypothesis No.3: Association between site supervision adequacy and the reduced odds of fatal accidents among craft workers with different experience/skill levels

The third hypothesis examines whether an association exists between site supervision adequacy and the reduced odds of fatal accidents across all experience level groups of craft workers. The analysis reveals that this association is statistically significant only among workers with low to moderate experience (0–3.99 and 4–9 years), where adequate supervision is associated with a reduced likelihood of fatal accidents. No statistically significant association was observed in the group of highly experienced workers (Table 6).

Table 6. Hypothesis testing results on the association between site supervision adequacy and the reduced odds of fatal accidents in craft workers with different skill/experience levels

Group number	Experience (years)	Number of accidents	No. Fatal No. Non-Fatal Fatal/Total Odds Ratio	Site Supervision		Pearson chi-squared test		
				Inadequate	adequate	value	df	p-value
1	(0-3.99)	3988	Fatal	797	239	5.655	1	0.009
			Non-Fatal	2160	792			
			Fatal/Total	27.0%	23.2%			
			Odds Ratio	1.22				
2	(4-9)	1002	Fatal	133	29	7.255	1	0.004
			Non-Fatal	604	236			
			Fatal/Total	18.0%	10.9%			
			Odds Ratio	1.79				
3	> 9	1346	Fatal	154	48	1.851	1	0.1
			Non-Fatal	819	325			
			Fatal/Total	15.8%	12.9%			

3.4. Hypothesis No.4: Association between site supervision adequacy and the reduced odds of fatal accidents among craft workers of different age

The last hypothesis examines whether an association exists between site supervision adequacy and the reduced odds of fatal accidents across all age groups of craft workers. The analysis shows that this association is statistically significant only in the younger age groups (15–24 and 25–34 years), where adequate supervision is linked to reduced accident severity from fatal to non-fatal. No statistically significant association was observed in the older age groups (Table 7).

Table 7. . Hypothesis testing results on the association between site supervision adequacy and the reduced odds of fatal accidents in craft workers of different age groups

Group number	Age range	Number of accidents	No. Fatal No. Non-Fatal Fatal/Total Odds Ratio	Site Supervision		Pearson chi-squared test		
				Inadequate	Adequate	value	df	p-value
1	15-24	1794	Fatal	456	110	15.083	1	0.000
			Non-Fatal	884	344			
			Fatal/Total	34.0%	24.2%			
			Odds Ratio	1.61				
2	25-34	2360	Fatal	337	98	3.293	1	0.039
			Non-Fatal	1410	515			
			Fatal/Total	19.3%	16.0%			
			Odds Ratio	1.26				
3	35-44	1253	Fatal	171	53	0.465	1	0.277
			Non-Fatal	763	266			
			Fatal/Total	18.3%	16.6%			
			Odds Ratio	1.12				
4	45-54	625	Fatal	74	30	0.090	1	0.431
			Non-Fatal	363	158			
			Fatal/Total	16.9%	16.0%			
			Odds Ratio	1.07				
5	55-64	249	Fatal	30	18	1.724	1	0.128
			Non-Fatal	145	56			
			Fatal/Total	17.1%	24.3%			
			Odds Ratio	0.64				
6	65-75	55	Fatal	16	7	1.005	1	0.236
			Non-Fatal	18	14			
			Fatal/Total	47.1%	33.3%			
			Odds Ratio	1.78				

3.5. Internal Validation of Results

To assess the robustness of the findings and evaluate the impact of sample size on the chi-square test results, an internal sensitivity analysis was conducted. In this process, 25% of the original dataset (1,584 rows) was randomly selected using SPSS. The aim was to examine whether the statistical significance (p-value) and effect size (Odds Ratios) remained consistent with the results obtained from the full dataset. Consistency was determined based on the alignment of statistical significance and effect size across both datasets. Specifically, if both the p-values from the test and the evaluation were either above 0.05 or below 0.05, and if both Odds Ratios were either greater than 1 or less than 1, the Consistency column was marked as *Yes*. The results of this sensitivity analysis are presented in the following table:

Table 8. Sensitivity Analysis of Odds Ratios and P-Values for Different Demographic Groups

	Group Number	Range (Years)	Original Odds Ratio	Sensitivity Analysis Odds Ratio	Original P-Value	Sensitivity Analysis P-Value	Consistency
Education	1	0-5	1.33	1.7	0.000	0.003	Yes
	2	8-10	1.16	1.61	0.205	0.099	Yes
	3	12-18	1	1	0.540	0.513	Yes
Experience	1	0-3.99	1.22	1.67	0.009	0.002	Yes
	2	4-9	1.79	2.21	0.004	0.79	No
	3	>9	1.27	1.12	0.1	0.465	Yes
Age	1	15-24	1.61	1.83	0.000	0.009	Yes
	2	25-34	1.26	1.96	0.039	0.013	Yes
	3	35-44	1.12	1	0.277	0.548	Yes
	4	45-54	1.07	2.1	0.431	0.118	Yes
	5	55-64	0.64	0.83	0.128	0.605	Yes
	6	65-75	1.78	1.5	0.236	0.594	Yes

The sensitivity analysis confirmed the robustness of the findings across different groups in terms of education, experience, and age. While minor fluctuations were observed in the odds ratios, the overall consistency of the results suggests that the effect of site supervision on accident severity remains stable. This reinforces the reliability of the conclusions drawn from this study.

3.6. Discussion

The results of the first hypothesis suggest that the severity of an accident involving a craft worker is statistically associated with the adequacy of site supervision. Specifically, accidents under adequate supervision are more likely to result in non-fatal rather than fatal outcomes. However, the strength of this association may vary among different groups of craft workers depending on their individual capabilities and characteristics. Therefore, the remaining three hypotheses examined the statistical relationship between site supervision adequacy and accident severity across groups defined by three major performance-shaping factors.

The results of the second hypothesis testing indicate that a statistically significant association between adequate site supervision and reduced accident severity (i.e., lower likelihood of fatal outcomes) exists only among craft workers with low educational attainment (five years or less). In contrast, no such statistically significant association was found among workers with higher education levels. This does not suggest that site supervision is ineffective for these groups; rather, it reflects the findings of prior research by Karimi and Taghaddos, which showed that higher educational attainment itself is statistically associated with a reduced likelihood of fatal injury, potentially reducing reliance on external supervisory control. [36]. According to Reason, that means this performance-shaping factor can prevent exacerbating the consequences of unsafe acts/conditions by providing some safety barriers that hamper the adverse impact of some latent conditions (e.g., inadequate site supervision) on the system's defenses and barriers. [38]. In other words, the educational attainment of craft workers can compensate for some deficiencies generated due to inadequate site supervision. For instance, educated craft workers know better that while performing a risky task under higher pressure of work, making some specific mistakes can increase the severity of accidents to fatal injuries. They will reduce the pressure of work based on their judgment even if a site supervisor does not warn them.

A similar pattern is observed regarding the statistical association between site supervision adequacy and accident severity among craft workers with varying levels of skill and experience. Statistically significant associations were found only in the first two groups (0–3.99 and 4–9 years of experience), suggesting that adequate supervision is associated with a lower likelihood of fatal outcomes among trainees and semi-skilled workers. These findings align with previous research by Karimi and Taghaddos [36], [37], which indicated that the protective effect of work experience against fatal injuries is generally weaker than that of educational attainment. Among highly experienced workers (more than 9 years), no

statistically significant association was observed, possibly indicating that these individuals rely more on their own safety practices and less on external supervision.

The results of the final hypothesis testing indicate that, for craft workers aged 16–24 and 25–34 years, there is a statistically significant association between adequate site supervision and reduced accident severity (i.e., a lower likelihood of fatal outcomes). These age groups may also reflect the strongest combined effects of education and experience in shaping safety-related behaviors, which aligns with previous research suggesting that younger workers are more responsive to external safety interventions such as supervision. [36], [37] The point is that craft workers at these ages, in the current database, have low experience and educational attainment. A total of an average of years of schooling and work experience in group No.1 is 6.98 years (5.45+1.53). This amount for group No.2 is 10.11 years (6.35+3.76). Overall, the observed association between site supervision adequacy and accident severity appears stronger among younger age groups, where the combined influence of education and experience are more limited. In contrast, for older craft workers (age groups 3, 4, and 5), the statistical analysis did not indicate a significant association between supervision and accident severity. These groups had notably higher combined levels of education and experience (average totals of 11.91, 15.53, and 15.42 years, respectively), which can be associated with the development of internal safety practices that reduce reliance on external supervision.

In the group of older craft workers (65–75 years), the statistical analysis did not show a significant association between adequate site supervision and accident severity. While the odds ratio was relatively high (1.78), the number of observations in this group was limited, suggesting that the results should be interpreted with caution. Previous research [37] has suggested that age-related factors may diminish the effectiveness of conventional preventive measures, including those related to experience and education. Therefore, additional safety strategies (potentially more proactive or tailored to the needs of older workers) may be warranted in this group, in conjunction with site supervision.

The UK's Health and Safety Executive (HSE) defines the responsibilities of supervisors as including risk management, implementation of control measures, worker safety supervision, fostering a safety culture, and incident investigation. While, the U.S. Occupational Safety and Health Administration (OSHA) expects supervisors not only to fulfill these duties but also to actively encourage worker participation in hazard identification, provide safety feedback, establish communication channels for reporting safety concerns, and place greater emphasis on continuous training. Additionally, in small-scale projects, HSE allows indirect supervision through phone communication, provided that a responsible individual is present on-site. In contrast, OSHA generally mandates the physical presence of supervisors, even in such projects.[40], [41]

The current study highlights a significant statistical association between strict supervision and reduced incident severity, particularly among younger, less experienced, and lower-educated workers. This pattern aligns with OSHA's structured supervision model, whereas the more flexible HSE framework may require additional context-specific strategies for effective implementation. Importantly, the findings suggest that aligning supervisory responsibilities in safety regulations with the observed associations can help address fatality risks in high-risk groups. However, increasing the number of supervisors alone can not be sufficient; equipping them with both technical and interpersonal competencies appears essential for enhancing their potential impact.

One effective approach to optimizing supervision is integrating artificial intelligence (AI) tools into the supervisory process. The first recommendation involves adjusting the sensitivity of real-time AI-based monitoring systems according to workers' age, experience, and education levels to enhance focus on high-risk groups. The second suggestion is utilizing AI tools to analyze recorded images and videos of high-risk workers' safety behaviors, enabling the prediction of potential incidents. These insights would assist supervisors in adopting a more targeted and preventive approach toward vulnerable groups.

Implementing the study's findings in large-scale projects, where workers are constantly moving across extensive areas (potentially spanning multiple floors and separate spaces) may be challenging due to the shortage of supervisors and the vast scope of supervision. It is recommended that supervision shifts from a passive to a preventive model, focusing on monitoring the worksite rather than individuals in high-risk groups. This approach involves identifying and mitigating workplace hazards and movement risks for vulnerable workers while utilizing a centralized monitoring system to track unsafe behaviors. Conversely, in smaller projects where continuous on-site supervision is not feasible, the study's findings suggest delegating safety responsibilities to trained foremen and conducting toolbox meetings under virtual supervisory oversight. These strategies optimize the use of supervisory resources and enable the more effective implementation of the

study's recommendations.

The current study, based on statistical data, highlights the pivotal role of supervision in improving safety outcomes. This role can either be amplified or diminished independently or in combination with other influencing factors. Some previous research has emphasized the importance of safety training for supervisors [42], while others have identified supervision as a factor influencing the effectiveness of workers' safety training [43]. Previous studies have indicated that labor shortages can negatively impact construction site safety [44]. The findings of the present research expand on this issue by addressing it from two perspectives: the shortage of supervisors and the shortage of skilled labor. First, the results suggest that insufficient supervisory presence may contribute to the severity of safety incidents. Second, a lack of skilled workers may lead to the employment of less educated, inexperienced, and younger individuals groups for whom supervisory oversight plays a particularly critical role in preventing severe accidents. By integrating the findings of the current study with the literature review, it becomes evident that supervision is a critical element in the construction safety management system.

3.6.1. Practical Recommendations

When a construction project is forced to be executed under moderate/severe skilled craft shortage and/or shortage in qualified site supervisors, a project manager needs to allocate available resources more efficiently:

1) Craft workers with low educational attainment and experience level regardless of their ages must work under intensive site supervision.

2) Young craft workers (15-24 yr.) with middle and high-level of educational attainment and experience level can work under moderate site supervision. The education and experience of young workers are at the highest strength of fatal prevention. However, as many countries reported a high rate of fatality in this age group [37], reducing the intensity of site supervision for educated/experienced young workers should be done with caution.

3) The majority of construction craft workers are in the ages of 25-64 years old. If the level of education and experience in these groups of workers is average/high, they can work in a lower level of site supervision. Before making this decision, the project manager should examine the quality of their experience and education. Based on the quantity and quality of their education and experience, the intensity of site supervision can become moderate to low.

4) In old craft workers (65-75 yr.), regardless of their experience and education level, it is recommended that they always do tasks which no fatal injuries are expected due to the occurrence of any kind of human error or other active failures in a system.

5) In line with the concept of targeted supervision, the following policies are recommended to enhance the effectiveness of site supervision in preventing fatal accidents:

- Train site supervisors to focus on high-risk groups, particularly workers with low experience, low education, or younger age. Training should include recognizing overlapping risk factors such as excessive overtime, adverse weather conditions, working alone, unsafe co-workers, and hazardous work environments.
- In cases of supervisor shortages, avoid hiring workers with low experience, low education, or young age for high-risk tasks to minimize the need for intensive supervision.
- If inexperienced, young, or less-educated workers are hired, ensure they are closely monitored by assigning skilled supervisors alongside them.
- Implement a safety scoring system for workers based on their adherence to safe practices and past incident records. Adjust supervision intensity accordingly, ensuring workers with lower safety scores receive more oversight.
- Utilize technology such as AI-powered cameras, GPS tracking, and automated alerts to detect unsafe behaviors and high-risk conditions, allowing supervisors to intervene promptly.
- The above-mentioned factors should be used as criteria for evaluating contractors by employers or supervising companies. For example, the coordination between the number of trained supervisors and the number of high-risk

workers could serve as a criterion in the safety qualification assessment of contractor companies for participation in the project.

It should be noted that the main purpose of lowering the intensity of site supervision in some groups of craft workers is just to save resources (i.e., qualified supervisor, funds, time, etc.) and allocate them to craft workers who should be supervised more. What also should be noted is that the perceived risk of the work can dominate this decision. If project managers believe that an activity is so risky, they may decide to perform the work under intensive supervision regardless of the capabilities of craft workers.

3.6.2. Limitations and Future Research

One limitation of this study is the subjective nature of the supervision adequacy classification. The categorization relied on the professional judgment of labor inspectors rather than a standardized protocol or validated assessment tool. Although inspectors were trained professionals familiar with national safety guidelines and followed consistent criteria such as supervisor presence, qualifications, and safety enforcement, individual differences in interpretation or threshold for adequacy could have introduced some variability and non-systematic misclassification. This subjectivity may have affected the internal validity of the findings, potentially attenuating or inflating the observed association between supervision adequacy and accident severity. Future research would benefit from using standardized and validated assessment tools to minimize this variability and improve comparability across studies. For example, Salas and Hallowell have proposed objective indicators that can partially quantify supervision levels on construction sites [45].

A further limitation relates to the potential underreporting of non-fatal accidents, which is a well-documented challenge in occupational safety research. In construction, this issue is particularly prevalent among migrant workers, who may choose not to report non-fatal injuries due to concerns about job security, fear of employer retaliation, or limited access to medical and legal support. While this underreporting could affect the absolute values of accident frequencies in our dataset, it is reasonable to assume that the probability of underreporting is relatively uniform across different levels of site supervision. Therefore, the comparative findings regarding the impact of site supervision on accident severity remain robust.

Another limitation of this study is the reliance on Chi-Square tests and odds ratios to examine the relationship between site supervision and accident severity (the odds of fatal accidents). While this approach is statistically valid for detecting bivariate associations, it does not allow for the simultaneous control of confounding variables, which would be possible through multivariate methods such as logistic regression. Although key demographic variables such as age, education, and experience were available and considered in subgroup analyses, several other important predictors (such as unsafe behaviors, project type, weather conditions, safety training, nature of injuries, and use of protective equipment) were not included in the dataset. These missing variables, identified in prior research as major contributors to accident outcomes, limited the feasibility of building a comprehensive regression model. As a result, the findings should be interpreted as statistical associations rather than evidence of causality. Future research with richer datasets and multivariate analytical methods will be able to further clarify the independent effect of site supervision on fatal accident prevention.

Despite these limitations, the study provides a foundation for further investigations into the role of supervision in construction safety. Future research can build upon these findings by exploring the following directions:

- a) Comparing the impact of safety training and supervision: A comparative study could evaluate whether safety training or active site supervision has a greater impact on reducing accident severity and fatality rates.
- b) The impact of job tenure on the relationship between supervision and accident severity: Examining whether a worker's length of stay at a construction site affects the relationship between supervision adequacy and accident severity could provide deeper insights into risk exposure over time.
- c) Shifting from accident data to safety indicators: Instead of relying solely on accident records, future studies could assess how supervision influences safety perceptions and behaviors across different worker demographics, offering a broader perspective on workplace safety.
- d) Examining the impact of demographic factors on safety climate: Future research could explore whether workers' age, experience, and education levels influence their perceptions of safety climate. Understanding these differences could help develop targeted strategies to improve workplace safety culture.
- e) Assessing the influence of demographic factors on safety training outcomes: Investigating whether the

effectiveness of safety training varies across different age groups, experience levels, and educational backgrounds could provide insights into optimizing training programs for diverse workforce segments.

4. Conclusions

The main objective of this study was to empirically investigate whether adequate site supervision is statistically associated with reduced odds of fatal injuries among construction craft workers across different demographic and occupational groups. The analysis confirmed a statistically significant association in the overall dataset. However, subgroup analyses revealed that this association is not consistent across all groups. Specifically, the association was statistically significant only among workers with lower levels of education and experience, as well as younger age groups. Among more experienced and better-educated workers, no statistically significant association was observed, which reflects their greater capacity to manage risks independently of supervisory input.

The study also found a strong statistical association between adequate site supervision and reduced odds of fatal accident rates among younger craft workers. While education and experience are recognized factors in accident prevention, their levels in this group were relatively low in the current dataset, potentially limiting their protective effect. This may explain why supervision appears particularly impactful in providing additional safety barriers for younger workers. In contrast, among middle-aged workers (who generally possess higher levels of education and experience) the observed association between supervision and reduced fatality risk was weaker, possibly due to their enhanced ability to recognize hazards and apply protective strategies. Among older craft workers, the analysis did not show a statistically significant association, which may be related to age-related limitations outweighing the benefits of supervision.

A shortage of skilled craft workers has been a prevalent problem in the construction industry in many countries. Construction projects that are executed under skilled labor shortage conditions are at a higher risk of having fatal accidents. To deal with this common issue, project managers need to choose a productive approach. Hinze et al. argued that it is difficult to propose the best leading indicators as an ideal measurement of safety performance in various construction firms and/or construction projects [21]. In addition, because of the usual limitations in the availability of resources (e.g., experienced practitioners, funds) and other constraints such as time, top managers always need to choose a limited number of efficient management practices to achieve their desired safety performance in the actual project's circumstances. The result of this study indicates that providing adequate site supervision can be recommended, at least, as one of the most productive approaches to reducing fatalities in construction projects particularly those performed under skilled labor shortage conditions. Here are some reasons for this argument:

Reason believes that to avoid major accidents in a system (e.g., fatalities in construction projects), addressing latent conditions is a more productive approach compared to addressing active failures. [38].

Site supervision is such a latent condition that inherently encompasses a wide range of important higher-level latent conditions. While the owner and contractor's top management commitment to the safety (upper-level latent condition) can be largely exerted through site supervision, the commitment and competency of the project management team, consultant, and key subcontractors about safety issues (lower-level latent condition) also can be mainly perceived with site supervision condition. In other words, site supervision conditions can simultaneously be a genuine representative of a wide range of very far to very close latent conditions in terms of their location and time to the sharp-end failures. Therefore, providing adequate site supervision in a worksite, in practice, means that some important upper-level latent conditions have been already addressed.

The site supervision contains many features from current prevalent safety management perspectives which are safety risk assessment, precursors analysis, safety leading indicators, and safety climate. Regarding Swiss Cheese model, this situation hinders the alignment of active failures related to the sharp end of a system and latent conditions and hence diminishes the risk of fatal accidents in construction projects substantially.

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